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MODE LOCKED FIBER LASERS AND THEIR APPLICATIONS

KJT, Inc.

Kenneth J. Teegarden

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13. ABSTRACT (Maximum 200 words)
This work has resulted in the development of a compact self-starting modelocked erbium fiber laser. The remarkable feature is the elimination of the need for any type of polarization control. Furthermore, all of the components are passive and are contained within the fiber cavity medium itself. This permits an ultra compact modular system that is portable. The laser employs a Fabry-Perot cavity with a fiber grating as one reflector, and a nonlinear multiple quantum well saturable absorber as the other. It operates at low pump power from a LD and produces pico second modelocked pulses with peak powers of over 20 W. When the saturable absorber is sized to a sub-millimeter dimension and micro-assembled on the fiber tip, all need for alignment is removed and the system is completely portable and fairly rugged. The transform limited chirp free characteristics of the ultra short pulses enable soliton propagation effects to minimize pulse broadening that limits the rates/distance in all present systems. These fiber lasers are presently suitable for device diagnostics, but may ultimately prove superior to the laser diode sources presently used in all high rate fiber optic communication and sensor systems.

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I.0 Introduction

Presently, ultra-fast TDM is limited by the availability of a compact, short-pulse source that is directly compatible with fiber coupled modulator technology. Fiber laser signal sources possess several significant advantages over established diode laser technology. The pico second and sub-pico second pulse widths achievable in fiber lasers are significantly shorter, allowing more efficient use of the full bandwidth available from single mode fiber. The wavelength region and configuration of fiber based lasers are inherently compatible with fiber amplifier technology, thereby greatly facilitating compensation for the distribution and splitting losses encountered in practical systems. Finally, nonlinear soliton type pulse generation and shaping in a fiber can be achieved naturally and can be designed to minimize dispersion induced limits experienced by all fiber systems at the bit rates required by the next generation of communication systems.

Up to now the design of fiber lasers has emphasized ring configurations rather than linear cavities because the latter required the use of bulk external reflectors which were difficult to incorporate into optical fiber systems. The advent of fiber grating technology has radically changed this situation. The imprinting of phase gratings into the core of single mode fiber is now a well developed technology.[1] By using ultraviolet light to increase the index of refraction of the core, it is possible to produce Bragg gratings with a wide range of reflectivities and band passes of several nanometers at wavelengths of high fiber transparency, particularly in the telecommunications window at ~1.55 microns. Fiber lasers employing fiber gratings have already been constructed. To date most of this work has concentrated on the development of short, single frequency fiber lasers using gratings with very narrow band passes. These surpass semiconductor DFB lasers in spectral purity.[2] However, the band pass of optically imprinted gratings can also be made large enough to sustain transform limited mode locked operation at pulse widths of the order of picoseconds in long fiber lasers with closely spaced temporal modes. For example, a grating with a band pass of 1.0 nm which is readily obtainable in practice can sustain transform limited pulse widths of about 2.52 ps. In addition, the operating wavelength of the laser can be selected by choosing the center wavelength of the grating. Thus a tunable mode locked fiber laser is possible over the entire gain curve of erbium doped

fibers or approximately 30 nm.

As will be shown, these mode locked linear cavity lasers have additional important advantages over ring lasers. For example they require no polarization controllers or isolators in the cavity, and are much less sensitive to residual birefringence and hence are inherently more stable. they also can be operated at low pump powers, easily obtainable with small semiconductor diode lasers. Because of the above characteristics, linear cavity lasers are compatible with commercial or military applications requiring compact, rugged, and tunable short pulse light sources with high peak powers.

This report summarizes results obtained to date on ring lasers and describes the design, construction, and characterization of two new compact mode locked erbium fiber lasers. These lasers employ a Fabry-Perot cavity with a fiber grating as one reflector and a second reflector constructed either from a multiple quantum well saturable absorber or a ring cavity. They require pump powers of 50 mW or less and produce mode locked pulses of picosecond duration. The peak power of the output pulses is from 10 to 40 watts. The laser using the saturable absorber as a mode locker operates at a repetition rate of about 3.0 MHz while the ring cavity increases the output frequency to 41.25 MHz.

2.0 Results

2.1 Summary of Ring Laser Results

Mode locked ring lasers based on erbium doped single mode optical fibers have have been the subject of intense study for the past few years. Both passive and active mode-locking techniques have been employed. Some of the first successful passively mode-locked lasers were based on a "figure eight configuration" which employed a fiber splitter as a non - linear mirror.[2,3] Much of the work to date has concentrated on the operation of such lasers in the soliton region. More recently, it has been found that simpler single loop configurations containing a minimum of components can also be used to construct self starting mode locked lasers which produce pulses with picosecond widths.[4-10] This new generation of simple ring fiber lasers are potentially compact rugged sources of stable trains of short pulses for a variety of military and industrial applications.

We described such a laser in an earlier report.[10] A schematic layout of the ring laser configuration used in that investigation is shown in Fig.1. The gain section of the loop was a Corning FiberGain module which contained a semiconductor laser pump operating at 980 nm coupled into about 20 m of erbium doped fiber through a wavelength division multiplexer. This module provided a maximum small signal gain of 30 db at a pump current of 200 mA or a launched pump power of about 50 mW. The rest of the ring was made of standard telecommunications fiber with minimum dispersion at 1.3 mm. Power was coupled out of the ring cavity by means of a fiber based splitter. The fraction of the power coupled out was varied from 70% to 10%. Unidirectional operation of the ring was obtained through the use of an isolator based on a pigtailed Faraday rotator. Both a polarization sensitive isolator and a polarization insensitive isolator were tried and found to give similar results. Control of the polarization state of radiation in the ring cavity was provided by either one or two conventional fiber based wave plates. In one case the laser was operated without these controllers and mode locking was achieved simply by slight adjustments of the position of the fiber external to the gain module. Again, no great difference in the characteristics of the mode locked pulses was observed. The temporal characteristics of the laser output were measured either with a fast detector-oscilloscope combination which had a band pass of 2 GHz or an autocorrelator. The optical spectrum of the output was obtained with a conventional spectrum analyzer and the average output power of the laser as a function of pump power was measured with a power meter having a time constant of 1.0 ms.

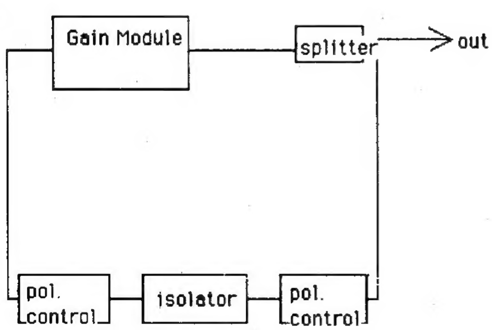


Fig. 1 Experimental layout of a ring laser.

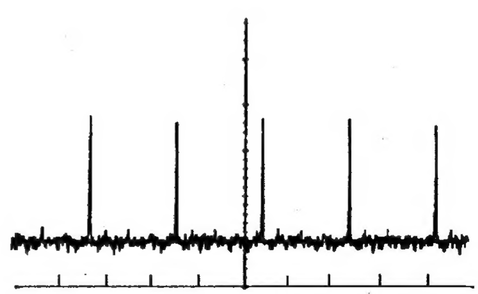


Fig. 2 Mode-locked pulse train. One division equals 50 ns. The period of the pulses was190 ns

The temporal behavior of the laser output is summarized in Figs. 2-5. Careful adjustment of the polarization controllers resulted in the mode locked pulse train shown in Fig 2. The period of these pulses was proportional to the total length of the fiber in the ring. This Fig. illustrates the relatively low repetition rate encountered in these long cavity ring lasers. The duration of a single pulse measured with a fast sampling oscilloscope and a photodetector with a response time of about 100 ps was found to range between 1000 and 500 ps.

Auto correlation traces of the pulses are shown in Fig. 4 and 5 for both a polarization sensitive and polarization insensitive isolator. Assuming a hyperbolic sech line shape, the data in Fig. 4 yields a pulse width of 17.5 ps, measured at half maximum. The pulse width corresponding to the auto correlation trace shown in Fig. 5 is 12.6 ps. The difference between the pulse duration obtained from these measurements and the larger value obtained using a sampling oscilloscope illustrates one of the problems encountered in passively mode locked lasers, namely pulse "jitter" or a small random fluctuation in repetition rate. Because the data shown in Fig. 3 is an average performed over many pulses in the train, fluctuations in the repetition rate broaden the observed pulse duration. These fluctuations, of course do not affect the pulse width measured with an autocorrelator. From Fig. 3 we can conclude that jitter of the order of occurred in the output of this laser.

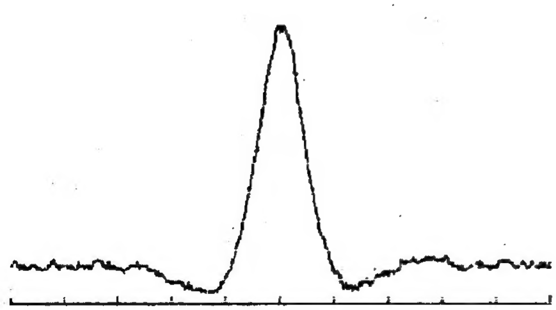


Fig. 4 Auto correlation trace of output pulses with polarizing isolator at a pump power of 50 mW. Each division equals 25 ps.

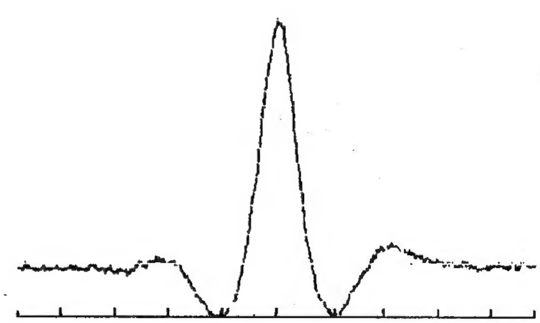


Fig 5. Auto correlation trace with non polarizing isolator at a pump power of 50 mW. Each division equals 25 ps.

The optical spectrum associated with the auto correlation trace shown in Fig. 4 is given in Fig. 6. When corrected for instrumental resolution, the full width at half maximum of this spectrum is 0.157 nm. At a peak wavelength of 1.56 μm, this corresponds to a frequency band width of 19.2 GHz. This result taken with the pulse width obtained from Fig. 4 yields a time bandwidth product of 0.34, very close to the value of .315 expected for a transform limited hyperbolic sech pulse shape.

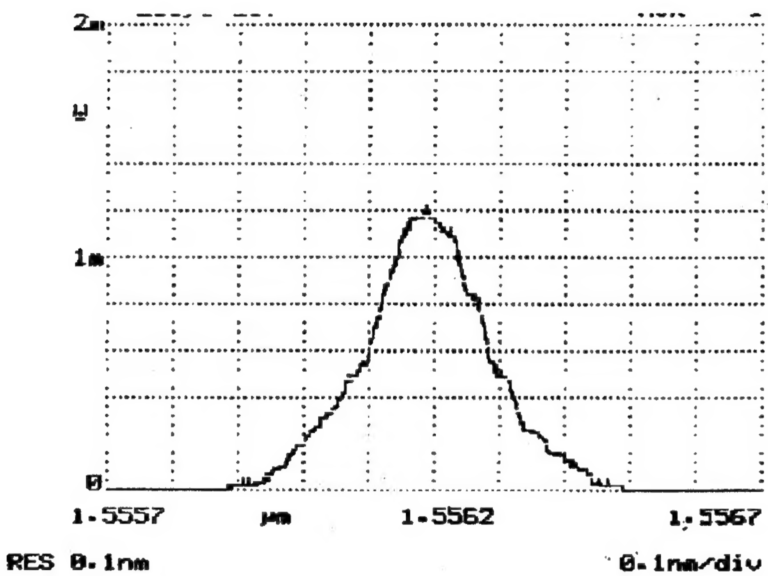
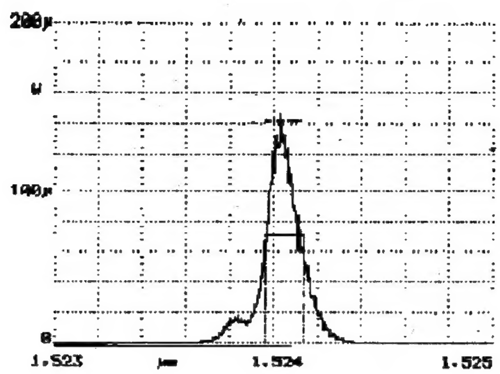


Fig. 6. Optical spectrum of pulse shown in Fig. 4

It is worth noting that the transition from DC operation to mode locked behavior could easily be determined from an observation of the optical spectrum on a real time spectrum analyzer. This is illustrated in Fig.7 where the spectra for DC operation and after mode locking was initiated are compared. The transition to mode locked operation was always marked by a rather dramatic increase in the spectral line width.



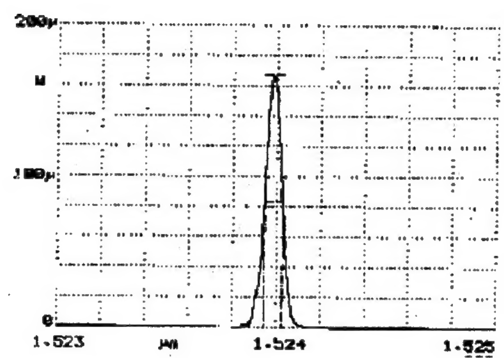


Fig 7. The upper trace is the mode locked spectrum of the laser, the lower trace shows the spectrum of the laser operating in the DC mode. Each division on the horizontal scale equals 0.2 nm. The instrumental resolution was 0.1 nm

2.2 Fiber Grating Linear Cavity Lasers

In the course of this contract we have developed linear cavity fiber lasers passively mode locked in two different ways. This work has resulted in an extremely stable laser design which is fiber integrated, rugged, and completely free of alignment and polarization sensitivity. The entire system can be enclosed in a 2x3x5 in package. The lasers use fiber gratings to determine the operating wavelength, and are passively mode locked with either a quantum well saturable absorber or a external ring sub cavity. They are completely self-starting, with a pump power requirement of only 40 mW in the fiber. This is to our knowledge the lowest pump power reported for such performance, and permits operation with standard compact cost effective 980 nm laser diode chips, in marked contrast to the multi stage pump diodes, Ti Sapphire pumped systems or

bulk type Nd-YAG (YLF) lasers generally used in recently reported ultra-short pulsed TDM applications.[14-16] The pulse width achieved in our laser is of the order of 10 picoseconds, corresponding to a potential system limit of 10 gigabits. One of the disadvantages of linear cavity mode locked fiber lasers for broad band telecommunications systems using time domain multiplexing is the low fundamental repetition rate due to the long cavity lengths (tens of meters) generally encountered in this type of laser when normal doping concentrations are used. Short cavities have been used in lasers developed for narrow line applications, and these can in principal be mode locked passively using a broad band pass filter and a saturable absorber as described below. The ultimate limit to the repetition rate that can be achieved by shortening the cavity is determined by the maximum concentration of erbium that can be doped into a silica based fiber before cooperative effects erbium ions reduce the pump efficiency or alter the emission spectrum. These effects apparently put a practical limit of about one meter on the minimum length of the cavity, corresponding to a maximum fundamental repetition rate of about 150 MHz. The use of an external ring cavity as the mode locker and output coupler in a linear cavity laser is one possible way of increasing the repetition rate of the mode locked pulses. Another problem with passively mode locked lasers is the relatively large amount of pulse jitter and CW background typically encountered in their output. Active mode locking is a way of substantially reducing these effects and at the same time increasing the repetition rate above the fundamental cavity frequency. As is reported below, our work on passive mode locking with quantum well saturable absorbers can easily be extended to allow active mode locking.

2.2.1 Fiber Laser Mode Locked with an External Ring

The test bed used to characterize the effect of terminating a linear fiber laser cavity with a fiber ring is shown in Fig. 8. To simplify construction, a commercial amplifier gain module was used as the gain medium. This module contained about 20 meters of erbium doped fiber pumped at 980 nm by a pigtailed semiconductor laser. the output of the module was terminated by a fiber grating while its input fiber was connected to a 50/50 fiber splitter and a fiber ring as shown. The length of the ring was typically 1.7 m.

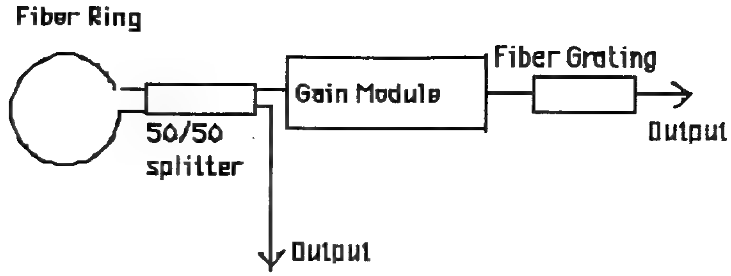


Fig 8. Experimental lay out of linear cavity laser terminated in a ring.

The fiber grating had a band pass of 0.2 nm and a center wavelength of 1.524 μm. Note that the band pass of the grating was large enough to permit transform limited mode locked pulses of about 16.5 ps duration. The output of this laser was found to consist of a train of pulses with a repetition rate of 41.25 MHz as is shown in Fig. 9. The length of fiber in the laser cavity, between the grating and 50/50 splitter was estimated to be 30 m. The calculated fundamental frequency of such a cavity of this length is close to 3.0 MHz. On the other hand, the fundamental frequency of the 1.7 m loop is 59 MHz, much closer to the observed repetition rate. Thus the short ring cavity apparently determines the repetition rate of the mode locked pulses and this laser has the potential of operating at a rate of several hundred MHz.

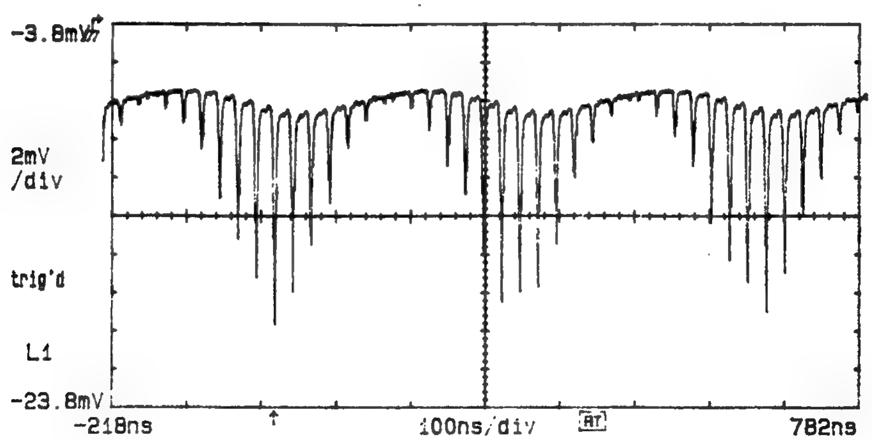


Fig. 9. Temporal output of the laser diagramed in Fig 8.

The optical spectrum of the laser output is shown in Fig. 10. Note that the measured line width was almost equal to the resolution of the scanning spectrum analyzer, or 0.1 nm, indicating that the temporal width of the output pulses was much larger that the minimum width permitted by the grating. In fact, auto correlation measurements indicated pulses widths of approximately 100 ps.

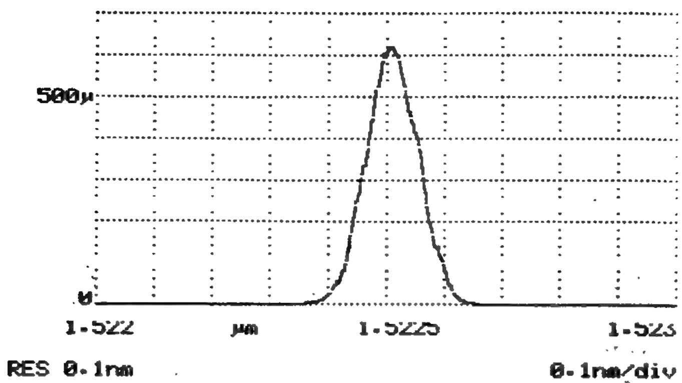


Fig. 10. Optical spectrum of the laser shown in Fig. 8

A second version of this laser included a paddle polarization controller in the ring. With this set up the controller could be used to change the output power of the loop from 6.0 mW to 4.0 mW. The controller appeared to act as a polarizer. When set to minimum power the output was very sensitive to small motions of the fiber in the loop.

In conclusion, the use of a ring reflector, in combination with a fiber grating to set the operating wavelength, seems to result in a mode locked laser which overcomes one of the shortcomings of long linear cavity lasers i.e. low repetition rate. Further investigation is needed to see how far this idea can be pushed. In particular, the reason for the long pulse duration needs to be determined.

2.2.2 Fiber Laser Mode Locked with a Quantum Well Saturable Absorber.

Ring lasers, and more recently linear cavity lasers, have been passively mode locked with semiconductor saturable absorbers. Both bulk semiconductors and quantum well devices have been used for this purpose. Passive mode locking with semiconductor micro structures is an attractive approach to mode locking it requires no additional source of power to drive the mode locker and, in principal, can easily be incorporated into fiber laser cavities. Although multiple quantum well saturable absorbers based on InAlAs/InGaAs and bulk InGaAsP have been successfully used to passively mode lock erbium doped fiber lasers in the past, they have not to our knowledge been used in conjunction with fiber gratings.[11,12] We have developed a particularly simple method of doing this which eliminates some of the complications of earlier schemes and which provides a method of selecting both the output wavelength and

pulse width.[13] The initial test bed used in this development is shown in Fig. 11.

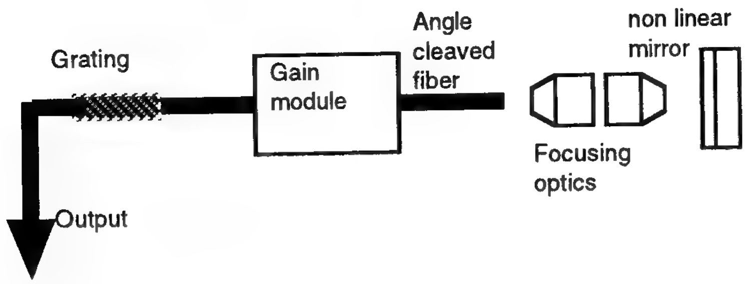


Fig. 11. Test bed for laser mode locked with a quantum well saturable absorber.

Again, to simplify the construction of the laser, the commercial gain module described above was used as the gain medium. This module contained about 20 m. of erbium doped fiber efficiently pumped at 980 nm by a pig tailed semiconductor laser. It had a maximum small signal gain at 1.53 μm of about 30 db, at a pump laser current of 200 mA which corresponds to approximately 50 mW of launched pump power. A fiber grating imprinted in a standard single mode telecommunications fiber was fusion spliced onto the input fiber of the gain module and served as one reflector in the standing wave cavity. The peak reflectivity of the fiber grating was 0.90 centered at 1.524 μm with a pass band of 0.20 nm. Outside of this region the grating was quite transparent.The output fiber from the gain module was angle cleaved to prevent back reflections and butt coupled to a semiconductor multiple quantum well saturable absorber which also served as the second mirror in the Fabry Perot cavity.

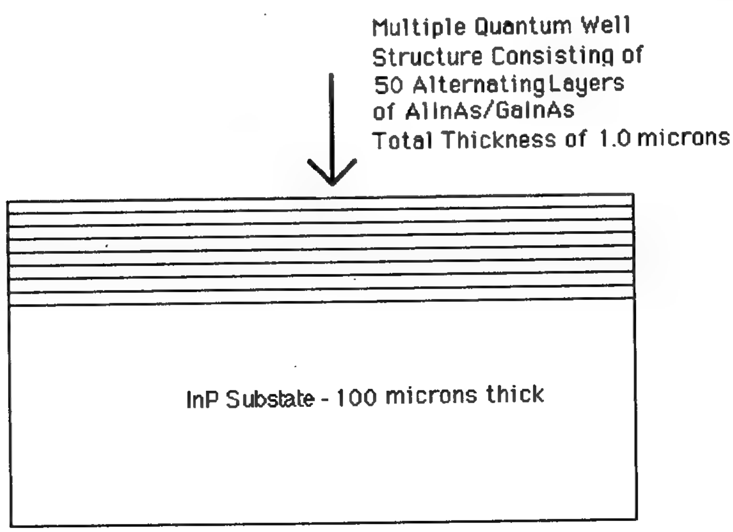


Fig. 12. The structure of the non linear mirror/saturable absorber.

The quantum well mirror (or absorber) consisted of alternating layers of AlInAs and GaAlAs deposited on a InP substrate as is illustrated in Fig. 12. The total thickness of these layers was 1.0 µm , while the substrate was 100 µm thick. The device was mounted so that the surface containing the quantum well structure was on the inside of the laser cavity. The linear transmission of this mirror is shown in Fig. 13. Note that the reflectivity at 1.524 vm, the operating wavelength of the laser, was approximately 0.18 for two surfaces or 0.36 for one surface. Since the mirror acts as the output coupler for the laser, and the faces of the mirror were not perfectly parallel, only about 0.36 of the output was fed back into the laser cavity.

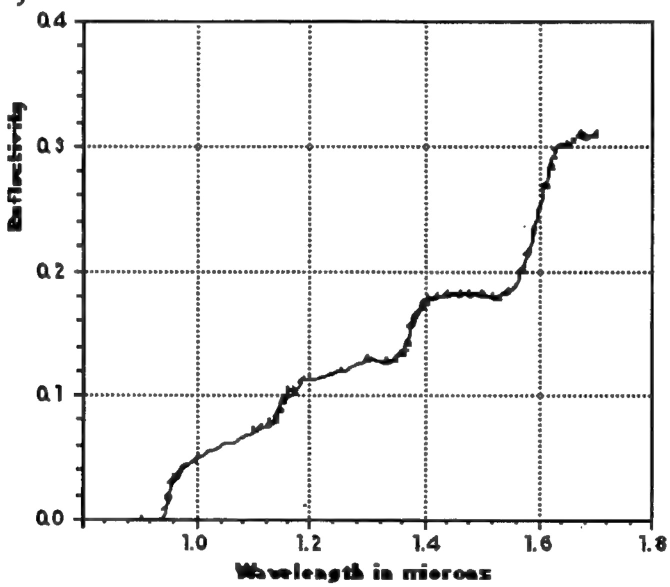


Fig.13 Reflectivity of the non linear mirror/saturable absorber.

Mode locking was very dependent on the lateral position of the quantum well mirror. Changes in position of the order of 10 µm could initiate or eliminate mode locked pulses. Measurements of the optical spectrum of the laser were made with a scanning spectrum analyzer with a resolution of 0.1 nm. The temporal behavior of the laser was observed either with a fast InGaAs photodetector or an autocorrelator. Most of these measurements were made through the fiber grating, as shown in the diagram. The laser actually emitted a higher power in the divergent beam emerging from the saturable mirror. This beam was collimated and some measurements of the output spectrum and temporal characteristics made with it. They did not differ from those measured through the grating. An average power of 2.0 mW was measured at this output. The temporal behavior of the laser as recorded by the fast photodetector is show in Fig.

14. The output consisted of a train of pulses with a repetition rate of 3.25 MHz and a period of 308 ns.

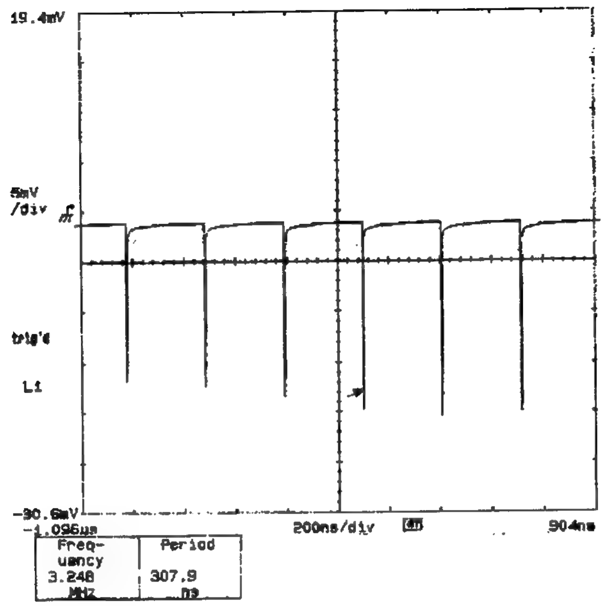


Fig. 14. Pulse train from laser mode locked with quantum well mirror

An auto correlation trace of the pulses is shown in Fig. 15. Assuming a

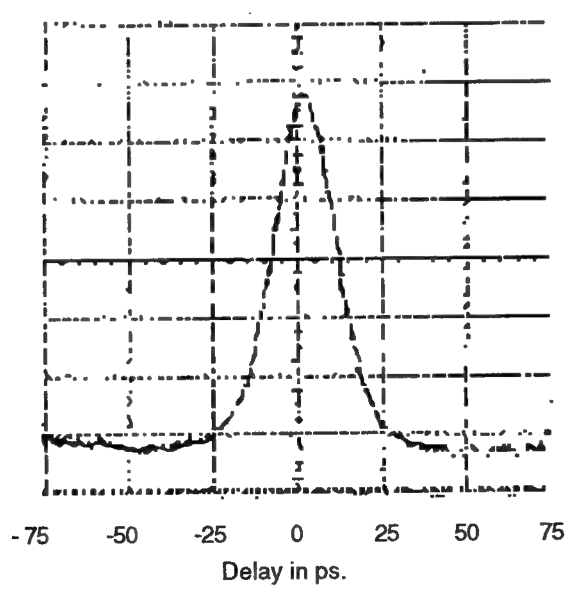


Fig 15. Auto correlation trace of the mode locked pulses. The grating band pass was 0.20 nm. The actual pulse width is 16.5 ps if a hyperbolic sech shape is assumed.

hyperbolic sech shape, the pulse duration works out to be 16.5 ps. The

corresponding spectrum is shown in Fig.16. When corrected for the 0.1 nm resolution of the scanning spectrometer,the line width turns out to be 0.15 nm. or 19.4 GHz. Thus the time bandwidth product for the mode locked pulses was 0.320, very close to the value of 0.315 expected for transform limited pulses with a hyperbolic sech shape.

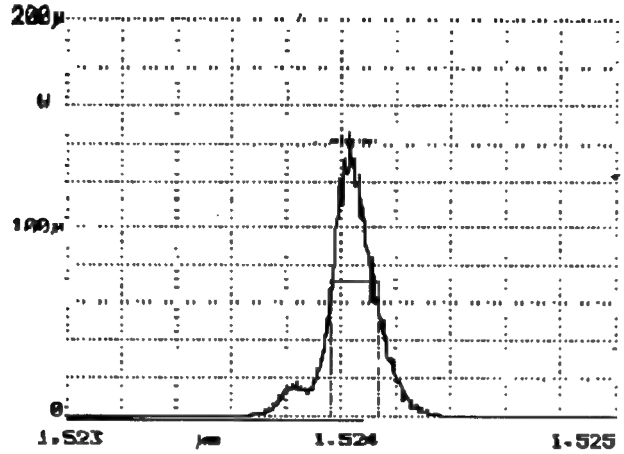


Fig. 16. Optical spectrum corresponding to the auto correlation trace shown in Fig. 16.

Control of both the pulse width and operating frequency of the laser by the grating was demonstrated by substituting a grating with a center resonance of 1556.5 nm and a line width of 1.6 nm. The auto correlation trace and optical spectrum of the pulses in this case is shown in Figs. 17 and 18. Note that the spectral line width was increased to 0.30 nm or 36 GHz, while the pulse decreased to 8.0 ps. The time band width product was thus 0.295, again close to the theoretical value. The operating wavelength of the laser was shifted to 1557 nm.

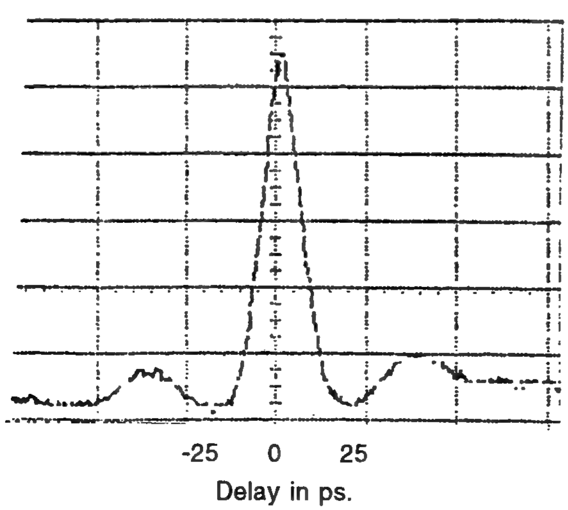


Fig. 17. Auto correlation trace of output pulses with a grating with a band pass of 1.6 nm. The actual pulse width was 8.5 ps.

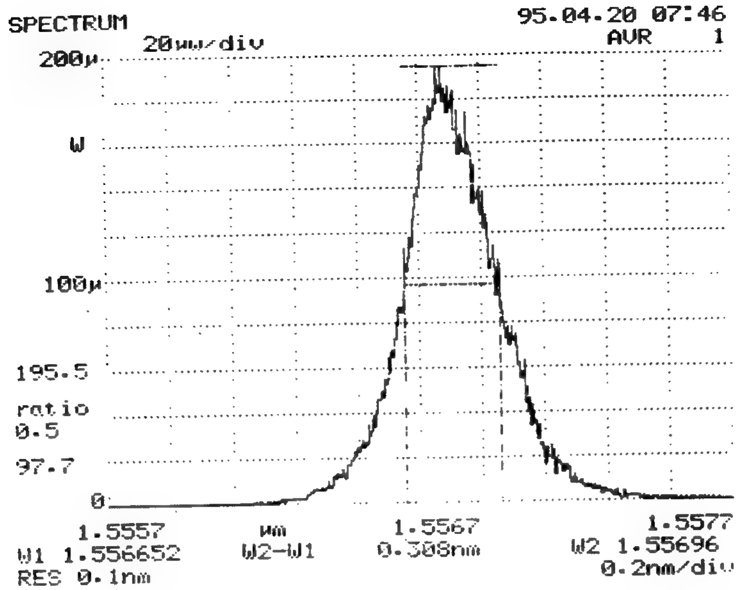


Fig. 18. Optical spectrum corresponding to the auto correlation trace shown in Fig. 17.

It should be noted that the low repetition rate of the mode locked pulses in these long cavity lasers results in a relatively high peak power for a modest average output power. If all the output power of the laser is going into pulses of width t and period t_f, the peak power is given by:

$$P = (t_f/t)P_{ave}$$

Using t ~ 10 ps, t_f = 300 ns and P_{ave} ~ 2.0 mW we find:

$$P = 60 \text{ W}$$

The peak power is reduced when a DC component is present in the output. If we assume that half the average power is DC, then the peak power is reduced to 30 mW.

3.0 Conclusions

From the results of this work and previous studies on ring cavity lasers we can conclude that simple ring cavity configurations can be used to construct passively mode locked fiber lasers which produce picosecond pulse widths at MHz repletion rates. We have demonstrated pulse widths of 12.6 ps at a repetition rate of 5.24 MHz. Although simple, these lasers have proven to be hard to align and keep aligned because the state of

polarization of the light in the cavity must be very precisely set by means of polarization controllers to initiate mode locking and produce short pulses. The polarization state in the cavity is extremely sensitive to birefringence in the fiber induced by very slight stresses or even temperature changes. Hence these environmental factors must be carefully controlled to maintain mode locking. Although ring cavity lasers are essential for some applications, they are not suited to situations where even slight vibrations or temperature shifts will occur.

Work under this contract has also resulted in the design and construction of two prototype mode locked erbium doped fiber lasers which are much more stable than the ring lasers described above. These lasers employ a fiber grating as one reflector in a simple linear Fabry Perot cavity. They are compact, rugged, and use readily available low power diode lasers as pumps. The wavelength of operation can easily be changed within the 30 nm erbium gain curve by choosing a grating with the desired center resonance. The duration of the mode locked pulses can also be selected by choosing the proper grating line width.

In one of these laser the second cavity reflector is a combination of a 50/50 splitter and a fiber ring. The length of the ring, which can be much shorter than the length of the linear cavity, determines the repetition rate or frequency of the mode locked pulses. A frequency of 41.25 MHz was demonstrated. This should be compared to the fundamental frequency of the linear cavity alone which was about 3.0 MHz. We can conclude, therefore, that this is a viable method of alleviating one of the disadvantages of fiber lasers, namely low repetition rate due to long cavity length. Unfortunately, the mode locked pulses produced by this laser were very long compared to those produced by a simple ring laser. Pulses of 100 ps duration were observed. Insufficient data was obtained to conclude whether or not this is an essential attribute of the laser or due to some easily adjusted parameter such as the length of the ring. Because of the other useful attributes of this laser it is felt that further testing is warranted.

An even more attractive candidate for a simple fiber based source of short pulse radiation around 1.55 μm was developed by using a multiple quantum well saturable absorber as the second reflector in the linear cavity described above. It was demonstrated that the design of such a laser could be greatly simplified by butt coupling the fiber cavity to the saturable

absorber rather than by focusing the light on the absorber. By choosing the appropriate gratings the laser was operated at wavelengths of either 1524 or 1557 nm. These wavelengths almost span the entire gain curve of the laser. In addition, the pulse duration was selected by changing the band width of the fiber grating. A factor of two difference in pulse width was demonstrated using this method. Before this design can be reduced to a practical laser, however, several potential problems need further study. The saturation flux of a saturable absorber is wavelength dependent. Thus the tuning range of a laser mode locked with a certain absorber may be restricted to a fraction of its gain curve. In addition, the width of the mode locked pulses is also dependent on the saturation flux of the absorber and hence will also be wave length dependent. While the linear absorbance of semiconductor saturable absorbers has been correlated with pulse width and operating wave length, detailed studies of their non linear spectral properties and how these can be optimized to produce the desired laser characteristics are needed. Furthermore, passively mode locked lasers tend to be subject to pulse frequency jitter, pulse amplitude fluctuations and CW background which can limit their usefulness in high speed communications applications. An analysis of these effects and the limitations they impose on the passively mode locked fiber laser must be carried out. One particularly attractive possibility for reducing these effects is to use a more advanced mode locking structure that is electrically controllable. In this structure an external voltage on the structure will apply an electric field across the quantum wells. Such electric fields shifts the quantum wells' absorption spectra and decreases the excitons' oscillator strengths via the Quantum Confined Stark Effect. Synchronizing voltage pulses on the quantum well structure with the mode locking pulses of the laser could greatly reduce timing jitter in the output pulses of the laser. A secondary use of these electrically controllable quantum well structures would be in voltage-controllable wavelength tuning of the laser.

It was found that mode locking behavior is very sensitive to the position of the cavity beam waist on the surface of the semiconductor. This effect has also been reported in the case of diode lasers mode locked with multiple quantum well devices, but to date no satisfactory explanation has been offered for it. In order for these devices to be used in practical lasers, an investigation into the origins of this effect should be undertaken.

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